

THE DISTANCE TO THE LARGE MAGELLANIC CLOUD

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ABSTRACT. A summary of recent Large Magellanic Cloud distance determinations μ_{LMC} is presented, with an eye towards pinpointing the source(s) of the resulting large discrepancies encountered between some of the techniques. Thirty-eight recent (1998-1999) measurements of μ_{LMC} are highlighted, the extrema for which (18.07 versus 18.74) are inconsistent with one another at the $\gtrsim 3\sigma$ level. The lack of overlap between the results of many of the techniques, simply employing the authors' quoted uncertainties, is a clear indication that unrecognized uncertainties, both random and systematic, plague many of the published results. While μ_{LMC} almost certainly lies within $\sim 13\%$ of 18.5 (i.e., between 18.20 and 18.75), to those of us outside the LMC "community", no single compelling argument has been put forth that reconciles the wildly disparate values presented thus far. A $\sim 13\%$ uncertainty in the LMC distance corresponds to a $\sim 13\%$ uncertainty in the Cepheid-based extragalactic distance scale.

1. Introduction

A precise (and accurate!) value of the distance modulus to the LMC, μ_{LMC} , is a crucial component of the current Cepheid-based extragalactic distance scale; μ_{LMC} provides the anchor against which *all* HST-based Cepheid distance determinations are measured. To date, both the *HST Key Project on the Extragalactic Distance Scale* (Gibson et al. 2000; Mould et al. 2000) and the *Sandage/Saha Type Ia Supernovae Calibration Team* (Saha et al. 1999) have adopted the "canonical" zero point of $\mu_{\text{LMC}}=18.50$ - the uncertainty in μ_{LMC} adopted by the *Key Project* was ± 0.13 mag (i.e., $\pm 6.5\%$), representing the largest component of their global systematic error budget. While ± 0.13 mag may be the formal uncertainty associated with the ensemble distribution of published μ_{LMC} values (in agreement with a similar analysis done by Jha et al. 1999), I hesitate to attach a high level of confidence to such statistical analyses since the individual μ_{LMC} "components" in the ensemble distribution are as different as apples and oranges, with an uncomfortable lack of internal consistency between the apples and apples (and oranges and oranges)!

In what follows, I present a cursory overview of current (mid-Oct 1999) thinking regarding the distance to the LMC, contrasting the techniques employed in determining μ_{LMC} , and commenting upon their respective strengths and weaknesses. The implications for the extragalactic distance scale are inexorably linked and noted in Section 3. Complementary recent reviews include Popowski & Gould (1999), Layden (1999), and Feast (1999).

2. The Distance to the LMC

Figure 1 summarizes the state of the field at the time of writing (mid-Oct 1999), and should be considered an updated, and somewhat more comprehensive, companion to Cole's (1998) Figure 1. Thirty-eight entries have been included here, and are displayed

in descending order of μ_{LMC} . The technique employed is listed to the right of each entry, along with a reference number matching those in the caption.

Taking the extrema at face value ($\mu_{\text{LMC}}=18.07$ and 18.74) demonstrates the gravity of the situation for the extragalactic distance scale. For example, assuming $\mu_{\text{LMC}}=18.50$, Gibson et al. (2000) derived $H_0=68 \text{ km s}^{-1} \text{ Mpc}^{-1}$; for $\mu_{\text{LMC}}=18.07$, though, $H_0=83 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and for $\mu_{\text{LMC}}=18.74$, $H_0=61 \text{ km s}^{-1} \text{ Mpc}^{-1}$ - i.e., H_0 could change by up to $\sim 20\%$, simply by revising the choice of μ_{LMC} !

A few general trends can be gleaned from a cursory inspection of Figure 1. First, methods based upon Cepheids and fitting to local subdwarf sequences *generally* tend to favor the “long” distance scale (i.e., $\mu_{\text{LMC}} \gtrsim 18.5$). Second, those based upon RR Lyrae statistical parallax and luminosity of the LMC red clump stars *generally* tend to favor the “short” scale (i.e., $\mu_{\text{LMC}} \lesssim 18.4$). Third, those based upon the exact same data (e.g., SN 1987A circumstellar ring geometry and the LMC eclipsing binary HV 2274) are disturbingly author-dependent.

2.1. Cepheids

The most extreme proponents of the long distance scale are Feast et al. (1998) and Feast & Catchpole (1997), with $\mu_{\text{LMC}} \gtrsim 18.7$. Their earlier value of $\mu_{\text{LMC}}=18.70 \pm 0.10$, based upon HIPPARCOS trigonometric parallaxes of Galactic Cepheids, coupled with the V -band photometry of Caldwell & Laney (1991), has been re-examined by three different groups and suggested to be too large by $0.13\text{--}0.38 \text{ mag}$. Madore & Freedman (1998) show that full multi-color photometry (adopting permutations of two to six photometric bands for various Cepheid subsets) leads to a downward revision of $0.13\text{--}0.36 \text{ mag}$. Oudmaijer et al. (1998) retain the single V -band photometry that Feast & Catchpole adopted, but apply a Lutz-Kelker bias correction to the parallaxes resulting in a 0.14 mag downward revision. Luri et al. (1998) employed their “LM” maximum-likelihood model (which incorporates proper motions μ , radial velocities v_{rad} , and trigonometric parallaxes π , into the mix, although π enters in with apparently minimal weight - Feast 1999) to revise Feast & Catchpole downward by 0.38 mag ; this represents the lowest Cepheid-based determination of μ_{LMC} , 18.35 ± 0.13 . In contrast with Luri et al., Feast et al. (1998), also using a sample culled by v_{rad} and μ , find $\mu_{\text{LMC}}=18.74 \pm 0.13$; the source of the discrepancy between the two studies is not readily apparent.

2.2. Subdwarf Fitting

Subdwarf fitting techniques give the distance to a globular cluster by matching the cluster sequence to a corresponding one derived from calibrating stars in the solar neighborhood; local subdwarfs with HIPPARCOS parallaxes provide the calibrating sample. Knowledge of the cluster’s distance then yields an absolute luminosity for the resident RR Lyrae (Popowski & Gould 1999, equation 18). Assuming a range of cluster metallicities spanning that of the LMC RR Lyrae can be sampled, one can derive μ_{LMC} . As Figure 1 shows, subdwarf fitting techniques generally lead to a μ_{LMC} consistent with the long distance scale. Reid (1997) and Caretta et al. (1999) claim $\mu_{\text{LMC}} \approx 18.55\text{--}18.65$, a consequence of which is that cluster horizontal branch stars are predicted to be $\sim 0.2 \text{ mag}$ more luminous than their field counterparts. Catelan (1998) has questioned the reality of this supposed cluster/field horizontal branch luminosity difference. Reid’s analysis leads to an extremely steep slope for the RR Lyrae $M_V\text{--}[\text{Fe}/\text{H}]$ relationship; his Figure 10

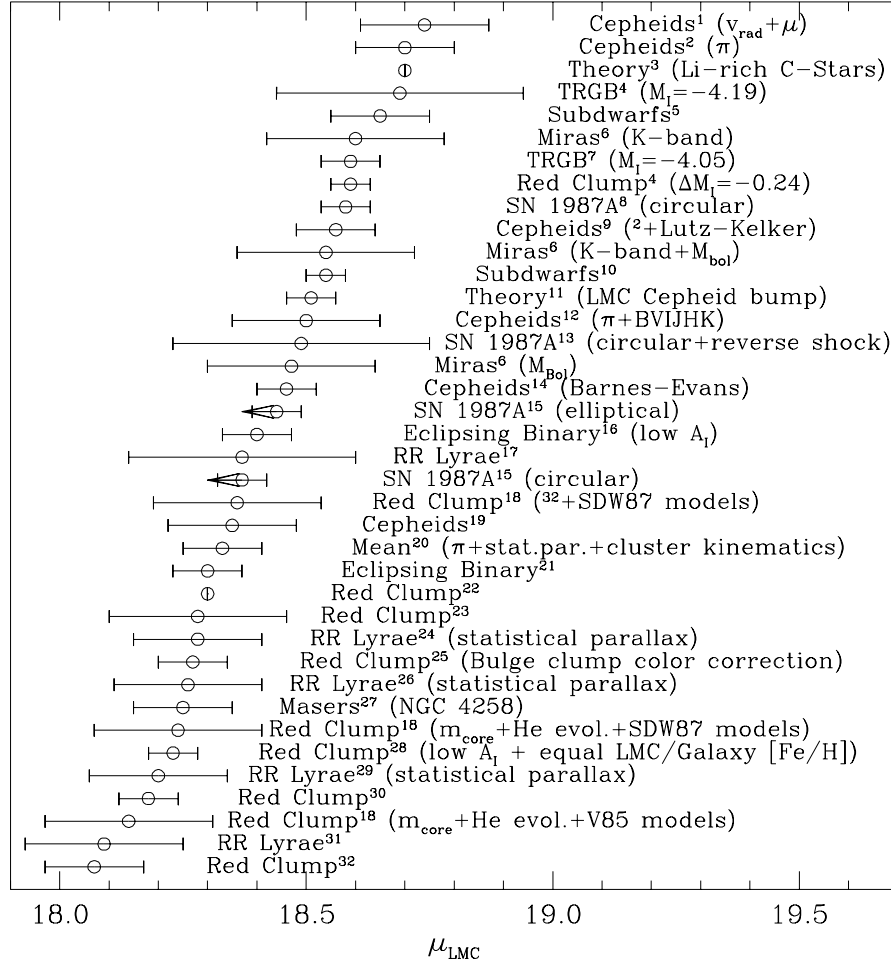


Fig. 1. Compilation of recent distance determinations to the LMC, presented in decreasing order of modulus μ_{LMC} . Cepheids, fitting to local Galactic subdwarf sequences, and theoretical stellar models tend to favor the “long” distance scale (i.e., $\mu_{\text{LMC}} \gtrsim 18.5$, while RR Lyrae, red clump luminosities, eclipsing binaries, and masers (indirectly, through NGC 4258) tend to favor the “short” scale (i.e., $\mu_{\text{LMC}} \lesssim 18.4$). References: ¹Feast et al. (1998); ²Feast & Catchpole (1997); ³Ventura et al. (1999); ⁴Romaniello et al. (1999); ⁵Reid (1997); ⁶van Leeuwen et al. (1998); ⁷Sakai et al. (2000); ⁸Panagia (1998); ⁹Oudmaijer et al. (1998); ¹⁰Caretta et al. (1999); ¹¹Wood (1998); ¹²Madore & Freedman (1998); ¹³Garnavich et al. (1999); ¹⁴Gieren et al. (1998); ¹⁵Gould & Uza (1998); ¹⁶Nelson et al. (1999); ¹⁷Luri et al. (1998); ¹⁸Cole (1998); ¹⁹Luri et al. (1999); ²⁰Popowski & Gould (1999); ²¹Guinan et al. (1998); ²²Beaulieu & Sackett (1998); ²³Girardi et al. (1998); ²⁴Layden et al. (1996); ²⁵Fernley et al. (1998); ²⁶Popowski (1999); ²⁷Maoz et al. (1999); ²⁸Udalski (1999); ²⁹Popowski & Gould (1998) and Gould & Popowski (1998); ³⁰Udalski (1998b); ³¹Udalski (1998a); ³²Stanek et al. (1998).

suggests a slope of 0.57 ± 0.35 , which seems difficult to reconcile with that observed in Galactic and M31 globular cluster systems (i.e., 0.18 ± 0.03 ; Fusi-Pecci et al. 1996). Gould & Popowski (1998a,b) and Popowski & Gould (1999) have stressed the influence of differing metallicity scales in the analyses as the primary source of the discrepancy between their “short” (faint horizontal branch ($M_V \approx 0.74$ at $[\text{Fe}/\text{H}] = -1.6$) and older ($t \gtrsim 16$ Gyrs) globulars) RR Lyrae scale and the Reid/Caretta et al. “long” (bright horizontal branch ($M_V \approx 0.47$ at $[\text{Fe}/\text{H}] = -1.6$) and younger ($t \approx 13$ Gyrs) globulars) scale. Pinsonneault et al. (1998) suggest that residual spatially-dependent systematic HIPPARCOS parallax errors should also be considered as a potential source of bias.

2.3. Statistical Parallax

Statistical parallax works on the principle that one can balance the stellar radial velocity distribution of a sample of Galactic RR Lyrae (distance independent) against that of its stellar proper motion distribution (distance dependent). The balanced velocity ellipsoids provide the necessary distance scale parameter, which in turns provides the necessary RR Lyrae absolute luminosity calibration. Statistical parallax, both prior to and subsequent to HIPPARCOS, has consistently supported the “short” distance scale (e.g., Layden et al. 1996; Gould & Popowski 1998a,b; Layden 1999).

2.4. Miras

Distances based upon linking Miras in the LMC with those in the Galaxy with accurate HIPPARCOS parallaxes, because they are based on such a small sample (11 overtone pulsators, culled from an initial total sample of 15 candidates - van Leeuwen et al. 1997), still have a large intrinsic scatter (± 0.18 mag) and suffer from a 0.13 mag systematic uncertainty depending upon the bandpass adopted. The ability to separate fundamental mode pulsators from overtone pulsators is also crucial, as any contamination by the former will systematically decrease the predicted μ_{LMC} .

2.5. SN 1987A

An appealing one-step technique which bypasses the intermediate assumption that various Galactic stellar constituents (e.g., RR Lyrae, Cepheids, Miras) are direct analogs to those in the LMC, is that based upon the geometry of the fluorescent light echo from the SN 1987A circumstellar ring. The technique consists of measuring the angular size of the ring with HST and comparing it to the absolute size, as estimated from the IUE emission line light curves. In terms of observables, the distance d can be written (after Panagia 1998):

$$d = \frac{c(t_o + t_{\text{max}})}{2 \tan R''} \quad [\text{cm}], \quad (1)$$

where $t_o = 86$ d is the onset of UV emission, t_{max} is the time of maximum UV line emission, and R'' is the apparent angular ring size at t_{max} . It is in the assignment of values to t_{max} and R'' where things start to get controversial.

Gould & Uza (1998) adopt the weighted mean of the Plait et al. (1995) HST [OIII] ring angular size determinations (i.e., $R'' = 0.858 \pm 0.011$ arcsec) and the IUE NIII] and NIV] light curves to derive $t_{\text{max}} = 378 \pm 5$ d. Panagia (1998) though attaches weight to the Jakobsen et al. (1991) 1988 pre-COSTAR [OIII] observation of 0.830 ± 0.015 , and uses this in combination with the Plait et al. data to extrapolate back to t_{max} , yielding

$R'' = 0.808 \pm 0.017$. Panagia claims the ring radius grew in extent by 6% between 1988 and 1993, while Gould & Uza assume a static ring. Panagia uses the CIII], OIII], and NIII] IUE light curves and favors $t_{\max} = 395 \pm 5$ d. Both t_{\max} solutions, despite being formally inconsistent at the 2σ level, look equally good to the eye. Adopting their respective values, we can use equation 1 to derive $\mu_{\text{LMC}} = 18.37 \pm 0.05$ (Gould & Uza 1998) and $\mu_{\text{LMC}} = 18.55 \pm 0.05$ (Panagia 1998 - aside: Panagia applies a $+0.03$ shift to this value, under the assumption that SN 1987A lies 700 pc in front of the LMC's center of mass). One-third of the resulting 0.18 mag discrepancy is due to the different t_{\max} adopted, with the remaining two-thirds due to R'' . If the ring is intrinsically elliptical, as suggested by Crotts (as cited by Gould & Uza), both teams' μ_{LMC} may be underestimated by up to 0.07 mag. The recent H α +NII observation of the reverse shock by Garnavich et al. (1999) has not (yet) clarified the above controversy.

Gould & Uza claim that these μ_{LMC} determinations are only *upper limits*, due to the inherent “prompt response assumption” employed (i.e., that no time delay exists between the blast of ionizing photons impinging upon the ring and the subsequent UV fluorescence). This fact has been used to reconcile the inferred SN 1987A-based μ_{LMC} with the lower value derived via the LMC's red clump and masers in NGC 4258 (discussed below), which both yield ~ 18.25 . What is not appreciated in these arguments is the magnitude of the putative time delay needed. Specifically, from equation 1, $\Delta\mu_{\text{LMC}} \approx -0.005$ mag for every day of “delay”, independent of R'' .

In practice, what this means is that to reconcile Gould & Uza's results (assuming an intrinsically circular ring) with $\mu_{\text{LMC}} = 18.25$, one would need to reduce t_{\max} from 378 to 357 d (i.e., a time delay of 21 d). The situation is even worse when attempting to reconcile Panagia with $\mu_{\text{LMC}} = 18.25$; in that case, t_{\max} would have to be reduced from 395 to 331 d (i.e., a time delay of 64 d). Are delays of this enormous magnitude physically feasible? I have not seen this particular scenario addressed, but an informal polling of my colleagues with experience in such fluorescence models suggests not - “a few days” was the most optimistic response, meaning the downward correction to μ_{LMC} could be no more than ~ 0.01 – 0.02 mag. Relaxing the prompt-response assumption, therefore, does not appear to be the panacea it might at first appear to be. Continuing to refer to the SN 1987A results as “upper limits” is somewhat misleading, in my opinion.

2.6. Red Clump

Under the assumption that the mean I -band luminosity of red clump stars in the LMC matches those calibrated locally by HIPPARCOS, Udalski (1998b) and Stanek et al. (1998) found $\mu_{\text{LMC}} \approx 18.1$. Cole (1998) criticized these analyses on the basis that age and metallicity differences between the LMC and Galactic red clump stars cannot be neglected. By employing Seidel et al. (1987) red clump models, evolved under the (poor) assumption of constant helium abundance and core mass, Cole claimed that Udalski and Stanek et al. underestimated μ_{LMC} by 0.28 mag. This extreme correction though is not supported by modern stellar evolution models (e.g., Girardi et al. 1998). In fact, even in comparison with its contemporaries (e.g., VandenBerg 1985; Lattanzio 1986; Sweigert & Gross 1978), the Seidel et al. models are extreme. Adoption of any of the other models of that era would have led to a predicted correction factor of 0.1 ± 0.1 , as opposed to the ~ 0.3 suggested by Cole. Empirically, Stanek & Garnavich (1998) show that the

stellar populations in three M31 fields have identical I -band luminosities. Considering the galactocentric distances of the fields (6.7, 11.2, and 33.6 kpc) with the Zaritsky et al. (1994) abundance gradient (-0.018 dex/kpc), one would predict an *a priori* metallicity differential of ~ 0.5 dex, in agreement with each field's CMD (Holland et al. 1996; Rich et al. 1996). In the parlance of Cole, this 0.5 dex difference implies that there should be a 0.15 ± 0.05 mag difference in the I -band luminosities of the inner and outer M31 field CMDs - such a difference is not observed. Further evidence to the minimal role played by age differences is provided in Udalski (1998b), who showed that the I -band luminosities of LMC and SMC clusters was independent of age (for cluster ages of ~ 2 – 10 Gyrs).

More recently, both Zaritsky (1999) and Romaniello et al. (1999) have suggested an upward revision of ~ 0.2 mag be applied to all previous red clump determinations, based upon their more sophisticated treatment of dust in the LMC red clump fields. In response, Udalski (1999) bypasses the complicated dust corrections favored by Zaritsky and Romaniello et al., by simply restricting the analysis to regions of low extinction, thereby obviating any complicated dust corrections. Udalski also makes the point that the region in which Romaniello et al. restricted their red clump analysis is unsuitable for red clump studies. Of perhaps even greater importance, Udalski culled from the HIPPARCOS Galactic red clump catalog, a large sample of stars *with LMC metallicities* (from McWilliam 1990), thereby avoiding any potential Galactic versus LMC stellar population mismatch pitfalls. His result - $\mu_{\text{LMC}} = 18.23 \pm 0.05$ - appears to be the most solid empirical application of this technique possible, at this time.

2.7. Tip of the Red Giant Branch (TRGB)

Romaniello et al. (1999) and Sakai et al. (2000) have derived $\mu_{\text{LMC}} \approx 18.6$ – 18.7 , based upon the apparent magnitude of the TRGB, coupled with the assumption that the I -band luminosity of the TRGB (for the LMC's metallicity) corresponds to $M_I \approx -4.1 \rightarrow -4.2$. Udalski (1999) has already commented upon the suitability and photometric calibration of the field employed by Romaniello et al.. To reconcile the Sakai et al. value of $\mu_{\text{LMC}} = 18.59$ with $\mu_{\text{LMC}} = 18.25$ would require $M_I \approx -3.7$.

2.8. Eclipsing Binaries

The geometry of the LMC eclipsing binary system HV 2274 has been used by Guinan et al. (1998) to derive $\mu_{\text{LMC}} = 18.30 \pm 0.07$. This technique, while not entirely geometrical (local reddening estimates are required), remains one of the most promising. A graphic illustration of the importance of using the appropriate reddening comes from the fact that Guinan et al. adopted a reddening of $E(B-V) = 0.12 \pm 0.01$, while in contrast, Nelson et al. (1999) derived a reddening of $E(B-V) = 0.09 \pm 0.03$, leading to $\mu_{\text{LMC}} = 18.40 \pm 0.07$.

2.9. Masers in NGC 4258

Under the assumption that $\mu_{\text{LMC}} = 18.50 \pm 0.13$, Maoz et al. (1999) derived a Cepheid distance to NGC 4258 of $29.54 \pm 0.12_r \pm 0.18_s$, where the subscripts 'r' and 's' correspond to random and systematic uncertainties, respectively. Conversely, Herrnstein et al. (1999) derived a purely geometric distance to NGC 4258 of $29.29 \pm 0.10_r \pm 0.12_s$, using the orbital motions of masers in the gas disk surrounding the galaxy's nucleus. Unless some unappreciated flaw exists in either (or both) of these analyses, in order to reconcile the Cepheid and maser distances, one must reduce μ_{LMC} from 18.50 to ~ 18.25 .

3. Summary

To re-iterate points made earlier, it is clear from even a cursory examination of Figure 1 that significant unappreciated systematic uncertainties exist in many of the published values of μ_{LMC} , as evident in the lack of overlap in the quoted uncertainties. I am loathe to pass judgment on the various entries shown in Figure 1, but will mention that those techniques deemed as “geometric” (and, in principle, somewhat less susceptible to intermediate steps in going from Galactic to LMC stellar populations), such as the eclipsing binary HV 2274, the circumstellar ring around SN 1987A (at least Gould & Uza’s analysis), and the masers in NGC 4258, all suggest $\mu_{\text{LMC}} \approx 18.3$. Cepheids (except for Luri et al. 1999) and subdwarf sequences still favor the long scale ($\mu_{\text{LMC}} \approx 18.5 - 18.7$). I remain skeptical that our understanding of μ_{LMC} is accurate to 6%, as has been assumed in most Cepheid-based extragalactic distance scale analyses, and would suggest that 13% is a fairer reflection of the present-day uncertainty. I stress that this 13% should *not* be construed in terms of any sort of Gaussian confidence level (e.g., 1σ , etc.); I do not currently support the use of μ_{LMC} distributions as useful statistical measures of the uncertainty in μ_{LMC} .

Future astrometric missions such as FAME (<http://aa.usno.navy.mil/FAME/>) and SIM (<http://sim.jpl.nasa.gov/>) should provide a definitive calibration for the absolute luminosities of Galactic Cepheid and RR Lyrae standard candles, and hopefully resolve the remaining discrepancies, one way or the other.

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I want to dedicate this paper to the memory of my good friend Charlene Heisler - you are sorely missed Charlene.

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